



Original Research Article

Operability Assessment Framework for Gravity-Based Wave Energy Converters Using Full-Scale On-Site Testing in Low-to-Moderate Nearshore Waves

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ABSTRACT

Gravity-based wave energy converters present mechanically simple and maintainable solutions for coastal and island environments; however, their operability under irregular, low-to-moderate wave conditions is not well documented. This research introduces a compact operability assessment framework and applies it in an initial full-scale on-site demonstration. Following construction and installation, gearbox-output flywheel rotational speed and generator terminal voltage were measured during separate, non-synchronised operational runs. The gearbox-output flywheel rotational speed ranged from 63 to 359 revolutions per minute, while a separate open-circuit, no-load run yielded terminal voltages between 11.23 and 20.36 V. Due to the lack of simultaneous acquisition of environmental and operational records, a quantitative wave-to-response relationship could not be established. The results confirm short-term mechanical and electromechanical operability but do not address load-deliverable power, power take-off efficiency, grid-integration compatibility, or deployment readiness. The primary contribution is a field-informed framework for assessing functional operability, rather than predicting regulated electrical output. The compact engineering proxy does not account for added mass, viscous drag, wave slamming, or multidirectional wave-group mechanics. Seasonal variability, long-term degradation, corrosion, and structural wear remain unexamined; therefore, synchronised load-connected measurements, multi-season monitoring, and extended marine durability testing are recommended.

KEYWORDS

Wave, Energy, Converter, Gravity, Operability, Nearshore, Rotation.

INTRODUCTION

Wave energy is a widely distributed marine renewable resource with particular relevance to archipelagic regions, but its practical value depends on whether a converter can operate under local sea conditions. Ribal *et al.* [1] produced a high-resolution assessment of Indonesian wave-energy resources and demonstrated pronounced spatial variability across the archipelago. Muchtar *et al.* [2] transformed multi-year reanalysis data into depth-consistent design parameters for a shallow tropical site and identified predominantly low-to-moderate conditions. Mithun *et al.* [3] combined resource assessment with technological criteria to identify feasible coastal hotspots. Xu *et al.* [4] integrated 45 years of high-resolution wave-climate modelling into a framework for converter deployment decisions. Sun and Wang [5] showed that long-term resource variability can materially change expected converter performance. Mahmoodi *et al.* [6] further demonstrated that climate-driven changes in wave conditions may affect long-term power performance. Together, these contributions provide the resource evidence needed to establish a site-specific operating envelope and justify the claim that converter performance depends on local sea conditions.

Technology selection is particularly important in mild wave climates, where devices optimised for energetic offshore conditions may operate inefficiently. Ahmed *et al.* [7] reviewed converters for mild and low sea states and identified device–resource compatibility, mechanical transmission, and multi-fidelity validation as central design requirements. Kumar *et al.* [8] demonstrated that point-absorber size and power take-off damping determine the useful operating bandwidth under low-to-moderate tropical sea states. Operability should therefore be examined within the wave-height and period range that prevails at the intended site, because these studies show that device performance depends on matching the converter to local conditions.

Resource characterisation must also be connected to hydrodynamic assumptions and experimental uncertainty. Lokuliyana *et al.* [9] quantified how spatial uncertainty in wave-resource models propagates into estimates of converter performance. De la Torre-Castro *et al.* [10] demonstrated that power take-off constraints and the selected description of the resource jointly influence performance estimates. Samuel *et al.* [11] reviewed the hydrodynamic factors governing the motion responses of floating breakwaters and wave energy converters. Cervelli *et al.* [12] showed that directional spreading in irregular waves can alter the predicted response of a direction-sensitive device relative to a monodirectional approximation. Beringer *et al.* [13] quantified experimental uncertainty and nonlinear effects in regular-wave testing. These sources show that a compact representation must either resolve or aggregate the physical and experimental effects that affect performance estimates.

The required modelling depth depends on the claimed output across the mechanical–electrical conversion chain. Stock [14] demonstrated that neglecting power take-off efficiency can distort predicted converter performance. Gao *et al.* [15] incorporated a wave-to-wire model into an economic model predictive control framework for energy maximisation. Ding *et al.* [16] coupled an oscillating-water-column chamber, turbine, and generator to predict electrical output and stage-by-stage conversion efficiency. Tan *et al.* [17] developed a computationally efficient spectral-domain wave-to-wire model for converter arrays. Saghi *et al.* [18] proposed a reduced-order framework linking local converter motion to hydraulic response and estimated electrical output for a modular nearshore device. These studies show that power prediction requires a sufficiently complete conversion chain, whereas bounded proxies can support operability screening.

Field testing is essential because environmental variability, installation conditions, mechanical losses, and component interactions cannot be represented completely in laboratory or numerical studies. Wang *et al.* [19] presented procedures for field testing and assessing ocean-energy converters. Xia *et al.* [20] developed a field-based conversion-efficiency method

that connects measured resource inputs to converter outputs and requires well-defined measurement boundaries. Nikolaidis *et al.* [21] combined laboratory experiments with field validation of a point absorber designed for a low-energy wave climate, while identifying short test duration as a constraint. Dragić *et al.* [22] measured several stages of the Sigma converter during sea trials to quantify power, efficiency, and transmission losses. Miškov *et al.* [23] examined slacking and snapping of the same converter's tension-leg-platform moorings, showing that mechanical reliability must be evaluated together with energy conversion. Okushemiya *et al.* [24] used field observations to validate and improve the power take-off model of a deployed converter with a tethered heave plate. Rollano *et al.* [25] evaluated full-scale, grid-connected UniWave200 data and calculated wave-to-grid efficiency from measurements spanning the capture and power take-off stages. Carrelhas *et al.* [26] developed procedures to estimate generator power and turbine torque during the modelling and field testing of oscillating-water-column converters. Chen *et al.* [27] reported model testing and a sea trial of a multi-absorber converter at megawatt scale. Collectively, these studies show that performance claims should remain consistent with the field measurement boundary because field data define what can be claimed.

Mechanical rectification offers one route for converting reciprocating wave-induced motion into unidirectional shaft rotation. Ariefianto *et al.* [28] experimentally demonstrated a cascaded-gear transmission intended to improve conversion under short-period waves. Wu *et al.* [29] combined one-way bearings, springs, and a flywheel to smooth generator rotation under irregular waves. Rezaei *et al.* [30] proposed a rectified rotary power take-off for transforming the relative motion of a two-body converter into unidirectional rotation. The same group subsequently quantified the effects of speed, friction, and electrical loading on a physical unidirectional transmission [31]. Gelos *et al.* [32] developed and experimentally validated a generalised model of mechanical motion rectifiers that explicitly represents coupling, disengagement, friction, and unidirectional power transmission. Yang *et al.* [33] evaluated the electrical-power potential of an active mechanical motion rectifier coupled to a controllable generator load. Earlier laboratory work by Muchtar [34] investigated sealed water-filled containers, counterweights, one-way mechanisms, and a common shaft under a controlled wave simulator.

Scaling from an individual unit to multiple converters introduces spatial interaction and phasing. Vervaet *et al.* [35] used wave-basin experiments to investigate hydrodynamic interactions in centrally controlled arrays under irregular short- and long-crested waves. Zou *et al.* [36] developed a method to evaluate array performance while accounting for the wave field perturbed by individual converters. Gong *et al.* [37] proposed an indicator to characterize array energy absorption under real sea states. Han *et al.* [38] optimised array layouts using realistic wave-climate information. These studies address hydrodynamic interaction, absorbed energy, or layout optimisation, but not the staggered mechanical engagement of spatially separated gravity-based units connected to a common shaft, so that claim remains unaddressed in the existing array literature.

Operability also has a durability dimension. Ziaei *et al.* [39] introduced health-sensitive control concepts that incorporate component condition and service life into converter operation. The same authors subsequently proposed reliability-driven control augmentation to balance energy maximisation against power take-off lifetime [40]. Lou *et al.* [41] compared dynamic mooring simulations with field measurements and evaluated anchor movement, fatigue, and extreme tension. Lindén *et al.* [42] demonstrated the importance of validated protection against corrosion, biofouling, and wear on converter components. Chulahwat *et al.* [43] incorporated climate-change and fatigue effects into converter-array optimisation. Together, these studies show that durability considerations should be included in the assessment of operability.

The investigated converter employs sealed, water-filled containers connected to a common shaft through phase-selective one-way mechanisms. During wave fall, an engaged container

descends and transmits gravitational torque to the shaft, whereas during wave rise, the mechanism disengages and the counterweight assists the return motion. Spatially separated units encounter different wave phases and may therefore engage the shaft at different times, supporting repeated unidirectional rotation. The incident wave field sustains the cyclic displacement; gravity is not treated as an independent energy source.

Although previous studies have addressed wave-resource characterisation, mechanical motion rectification, converter arrays, and field performance assessment, evidence regarding the operability of gravity-based, phase-selective, multi-unit architectures under low-to-moderate nearshore waves remains limited. Accordingly, this study develops and applies a compact operability assessment framework through a full-scale on-site test. The framework relates representative wave conditions, deployment depth, converter spacing, and enclosed seawater mass to an interpretable gravitational input proxy. Field operability is assessed using gearbox-output flywheel rotational speed and separately recorded open-circuit generator terminal voltage.

The study is limited to short-term functional operability. The pre-construction wave survey, rotational-speed run, and voltage run were not synchronised; therefore, the results do not establish a quantitative wave-to-response relationship, load-deliverable power, conversion efficiency, long-term reliability, or deployment readiness. Further validation requires synchronised load-connected measurements, multi-season monitoring, and long-duration marine durability assessment.

MATERIALS AND METHODS

The real nearshore full-scale test comprised two sequential, non-synchronous stages: a pre-construction survey for site selection and platform orientation, followed by post-installation measurements of gearbox-output flywheel rotation and generator response. This sequence defines the assessment boundary and prevents the pre-construction environmental observations from being interpreted as synchronous inputs to the operational records.

Study Design and Assessment Boundary

This study was designed as an initial full-scale field operability assessment of a gravity-based wave energy converter that had previously been evaluated under controlled laboratory conditions [34]. Its purpose was to determine whether the laboratory-demonstrated principle—vertical movement of sealed water-filled containers, phase-selective one-way engagement, and torque transmission to a common shaft—remained mechanically functional after installation in a naturally irregular nearshore environment.

The assessment boundary was restricted to short-term functional operability. Mechanical operation was examined through deployment observations and gearbox-output flywheel rotational-speed measurements to assess whether the mechanical transmission remained functional. Generator terminal voltage was recorded in a separate open-circuit, no-load run and used only as evidence that mechanical rotation reached the generator. The study did not include synchronised wave-motion-torque-electrical measurements, a regulated load, conversion-efficiency determination, grid-integration assessment, or long-term durability evaluation.

Operability Assessment Framework

Figure 1 illustrates the operating principle of one converter unit. A chain connects a sealed container filled with seawater to a phase-selective one-way mechanism mounted on the main shaft. A counterweight maintains chain tension and assists the return stroke. During a local drop in water level, the container descends, and the one-way mechanism engages, transmitting torque to the shaft. During a rising local water level, the counterweight assists the upward return, while the mechanism disengages and prevents reverse torque transmission. The incident

wave field therefore restores the cyclic displacement, whereas gravitational loading associated with the enclosed seawater mass supplies the principal driving term during the engaged downward stroke.

In the multi-unit configuration, individual containers are distributed along a common shaft and connected through separate one-way mechanisms. Adjacent containers encounter the propagating free surface at different spatial phases; their engaged strokes are therefore staggered rather than necessarily simultaneous. This spatial diversity is intended to distribute torque impulses over time. The shaft drives a gearbox coupled to an electric generator, while the main transmission components remain above the waterline to permit inspection, adjustment, and routine maintenance.

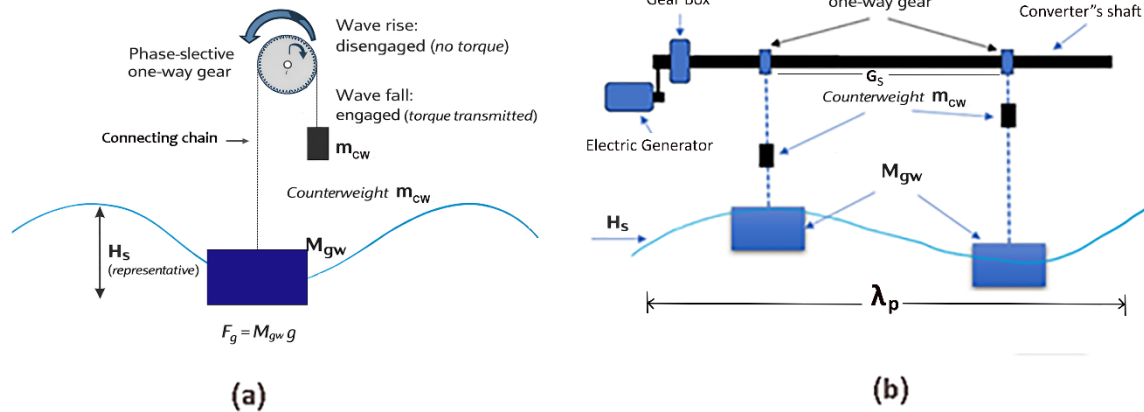


Figure 1. Operating principle of the gravity-based wave energy converter: (a) phase-selective engagement of a single water-filled container and counterweight system, and (b) spatially phased multi-unit configuration connected to a common shaft, gearbox, and generator.

Framework Formulation and Interpretation

The framework provides a compact engineering representation of the conditions that support mechanical engagement. The effective mass acting during the engaged downward stroke is defined by Equation (1):

$$M_{eff} = (M_{gw} + M_c) - m_{cw} \quad (1)$$

In Equation (1), M_{eff} is the effective moving mass, M_{gw} is the mass of seawater enclosed within the container, M_c is the effective non-water moving mass of the converter unit, and m_{cw} is the counterweight mass. The enclosed seawater mass used in Equation (1) is calculated using Equation (2):

$$M_{gw} = \rho V_w \quad (2)$$

Equation (2) relates the enclosed seawater mass to seawater density, ρ , and enclosed volume, V_w . The counterweight maintains chain tension and assists the return stroke. When the counterweight approximately balances the effective non-water moving mass, the enclosed seawater mass becomes the principal gravitational term during the engaged downward motion.

The gravitational input proxy used for operability interpretation is formulated in Equation (3):

$$W_{in} = \eta N_{eff} \left(\frac{\lambda_p}{G_s} \right) M_{gw} g H_s \quad (3)$$

In Equation (3), W_{in} is the gravitational input proxy, η is an aggregate factor representing unmeasured mechanical losses, N_{eff} is a normalised factor representing the influence of multi-unit spatial phasing, g is gravitational acceleration, H_s is the significant wave height, λ_p is the

peak wavelength, and G_s is the spacing between adjacent converter units. The phasing factor satisfies $0 < N_{eff} \leq 1$. This proxy is used only as an interpretive operability measure. Because η and N_{eff} were not calibrated from unit-resolved torque measurements, W_{in} must not be interpreted as measured shaft work, electrical energy, conversion efficiency, or load-deliverable power.

Equation (3) was not evaluated numerically because the aggregate loss factor and multi-unit effectiveness factor were not calibrated from unit-resolved torque and displacement measurements. Assigning nominal values would introduce false precision. The present field assessment therefore relies on directly observed operational indicators, while Equation (3) identifies the quantities requiring calibration in subsequent validation.

The peak wavenumber is obtained from the finite-depth dispersion relation given in Equation (4), following linear wave theory [44]:

$$\omega_p^2 = gk_p \tanh(k_p h) \quad (4)$$

Equation (4) is solved for the peak wavenumber, k_p , at the local water depth, h . The peak angular frequency used in Equation (4) is defined by Equation (5):

$$\omega_p = \frac{2\pi}{T_p} \quad (5)$$

Equation (5) relates the peak angular frequency to the peak wave period, T_p . The corresponding peak wavelength is calculated using Equation (6):

$$\lambda_p = \frac{2\pi}{k_p} \quad (6)$$

The wavelength obtained from Equation (6) is used to determine the phase separation between adjacent units through Equation (7):

$$\Delta\phi_p = k_p G_s = \frac{2\pi G_s}{\lambda_p} \quad (7)$$

Equation (7) expresses phase separation as a function of peak wavenumber and unit spacing. Together, Equations (1)–(7) relate representative wave descriptors, deployment depth, enclosed seawater mass, and converter spacing to an interpretable engagement pattern. They form a reduced-order engineering proxy, not a high-fidelity hydrodynamic model; added mass, viscous drag, wave slamming, and multidirectional wave-group effects are excluded from the formulation. Overall, the framework organises initial site and design information into a reduced-order basis for the operability assessment illustrated in Figure 2; however, it does not generate a calibrated power-performance curve.

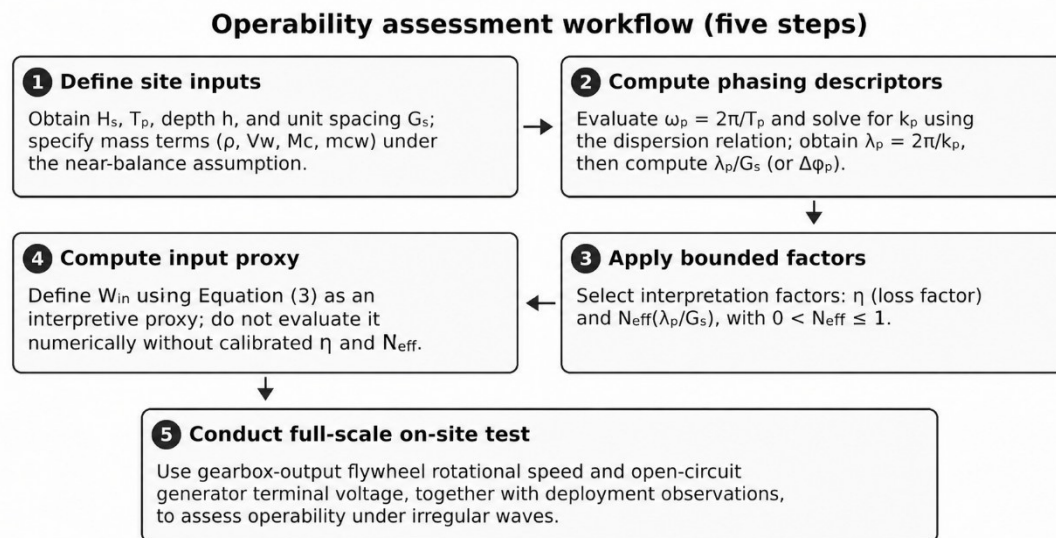


Figure 2. Workflow of the operability assessment framework

Full-Scale Converter and Field Site

The full-scale gravity-based wave energy converter was deployed in the nearshore zone at Kajuangin Beach, Sabbangparu Village, Pinrang Regency, South Sulawesi, Indonesia ($3^{\circ}32'54.93''$ S, $119^{\circ}30'34.64''$ E). The site is situated on the western coast of Sulawesi, with open water to the west and the shoreline to the east. The field programme was intended to determine whether the operating principle previously observed in the laboratory remained functional after full-scale construction and marine installation.

The full-scale converter comprised sealed, water-filled containers connected to a common shaft through individual phase-selective one-way mechanisms. During the falling-water phase, an engaged unit transmitted gravitational torque to the shaft. During the rising-water phase, the mechanism disengaged while the counterweight assisted the return motion. A gearbox coupled the common shaft to an electric generator. The main transmission components were positioned above the waterline to permit visual inspection and adjustment during the test. Figure 3 shows the deployment site, installed platform, and accessible mechanical components.



Figure 3. Full-scale nearshore deployment at Kajuangin Beach: (a) deployment site and installed platform, and (b) platform configuration showing the principal mechanical components above the waterline.

Pre-Construction Site Selection and Platform Orientation

Before platform construction, direct field observations were conducted between 09:00 and 12:00 local time on a single day to select a suitable deployment location and determine platform orientation. Two fixed reference stakes were installed in the nearshore zone. Their separation was measured in situ with a tape measure, and visible metric markers provided spatial references in the video frames. Free-surface motion was recorded with a Panasonic HC-V385 digital video camera at 25 frames per second, corresponding to a frame interval of 0.04 s.

The recordings were examined offline frame by frame in Adobe Premiere Pro. Crest-to-trough changes and successive oscillations yielded observed wave-height and dominant-period ranges of 0.20–0.50 m and 3–6 s. Incoming waves were observed to approach predominantly from the west and propagate eastward toward the shoreline, based on the visible movement of successive wave fronts relative to the shoreline and fixed site references. Because no directional wave instrument was used, the result is treated as an observed predominant direction rather than an instrument-resolved directional spectrum.

The observations were used for site selection and to align the platform's longitudinal axis and the spatial sequence of converter units approximately west–east, along the predominant direction of wave travel. The observed wave-height and dominant-period ranges provide preliminary environmental context for the assessment framework; they are not treated as long-term significant wave height or spectral peak period. They were not acquired simultaneously with the later rotational-speed or voltage records.

Operational Measurements

After platform construction and converter installation, rotational speed was measured at the flywheel located downstream of the gearbox using a non-contact digital optical tachometer. A reflective marker was attached directly to the flywheel to facilitate measurement. The reported values therefore represent the gearbox-output flywheel rotational speed rather than the rotational speed of the converter's main shaft. Fifty-two readings were obtained over a confirmed 250-min measurement window. Because the rotational-speed worksheet retained the observation order but did not include validated timestamps, the elapsed-time axis was uniformly reconstructed from 0 to 250 min, yielding a nominal separation of 4.90 min between observations. This axis shows temporal progression only and does not imply exact sampling times.

Direct-current (DC) generator terminal voltage was measured with a digital voltmeter under open-circuit, no-load conditions. The voltmeter display was recorded with the Panasonic HC-V385 camera at 25 frames per second, and 111 time-referenced voltage readings were extracted from the recording as evidence supporting the operational claim. Because current and true electrical power were not measured simultaneously with voltage, these values reflect only generator excitation. They cannot determine load-deliverable power, power-take-off efficiency, or grid-integration performance.

The pre-construction wave survey, rotational-speed run, and voltage run were non-synchronous. The records are therefore analysed as independent evidence supporting the operational claims. They cannot be used to establish point-by-point relationships among wave conditions, gearbox-output flywheel rotational speed, and generator terminal voltage. Figure 4 presents the measurement arrangements used in the two post-installation operational runs.



Figure 4. Measurement arrangements used in the two post-installation operational runs.

Data Processing and Presentation

The recorded rotational speed and voltage values were retained as raw observations for descriptive statistics and reporting the ranges. To clarify their temporal variation, a five-point centred moving average was superimposed on each raw series. Each trend value was calculated as the arithmetic mean of the corresponding observation, the two preceding observations, and the two following observations. Because a centred five-point window is unavailable at the ends of a record, the first two and final two trend values were omitted.

The moving-average curves were used only as visual guides. They were not used to replace the raw measurements, estimate energy production, or calculate converter efficiency. For the rotational-speed series, the elapsed-time axis was uniformly reconstructed over the confirmed 250-min measurement duration. Accordingly, 52 observations span 0–250 min with a nominal average separation of 4.90 min.

Given the short-duration and non-synchronous nature of the environmental and operational records, the analysis was limited to descriptive interpretation of functional operability; the results therefore indicate that only descriptive conclusions were appropriate. No inferential statistical testing, wave-to-response regression, or extrapolation to seasonal and long-term performance was undertaken.

RESULTS

The results are reported for the pre-construction site observations and the two post-installation operational runs. Because the wave survey, rotational-speed record, and voltage record were non-synchronised, they are treated as independent evidence rather than as a wave-to-response relationship.

Pre-Construction Site Observations

The pre-construction survey identified a nearshore location with observed wave heights of 0.20–0.50 m and dominant periods of 3–6 s. Incoming waves approached predominantly from the west and propagated eastward toward the shoreline, supporting an approximately west–east platform orientation.

These observations supported site selection and installation planning. They were not synchronised with the subsequent rotational-speed and voltage measurements and are therefore not used to estimate wave-to-shaft response, seasonal resource, hydrodynamic capture efficiency, or individual unit contribution.

Gearbox-Output Flywheel Response

Figure 5 presents 52 gearbox-output flywheel rotational-speed observations across the confirmed 250-min measurement window. The reconstructed elapsed-time axis has a nominal separation of 4.90 min between observations. The measured flywheel speed ranged from 63 to 359 rpm, with a mean of 198.96 rpm, a standard deviation of 76.89 rpm, and a median of 188 rpm. Every recorded value was above zero, confirming rotational output downstream of the gearbox at all 52 recorded observations; however, the response was neither steady nor regulated.

The five-point centred moving average ranged from 84.4 to 317.6 rpm. Mean flywheel speed increased from 150.04 rpm in the first half of the series to 247.88 rpm in the second half, while substantial short-term fluctuations remained. Because wave elevation, individual-unit engagement, and main-shaft torque were not recorded synchronously with the tachometer measurements, this difference cannot be attributed quantitatively to a particular wave height, period, or phasing event.

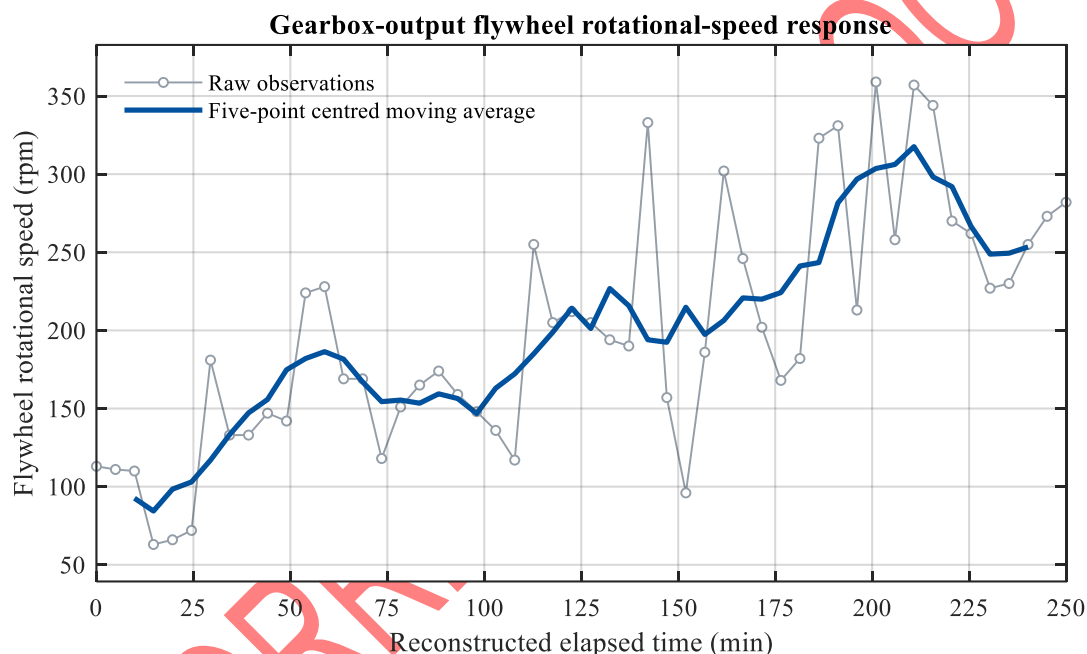


Figure 5. Gearbox-output flywheel rotational speed and five-point centred moving average during the 250-min full-scale on-site measurement run.

Open-Circuit Generator Response

Figure 6 presents 111 time-referenced voltage observations from the separate 110-min open-circuit run. Terminal voltage ranged from 11.23 to 20.36 V, with a mean of 15.95 V, a standard deviation of 2.12 V, and a median of 16.05 V. The five-point centred moving average ranged from 11.95 to 20.16 V. The mean voltage was 15.98 V in the first half and 15.91 V in the second half of the series.

A non-zero voltage was present in every extracted observation, documenting generator excitation during the field test. No simultaneous current measurement or electrical load was applied. Because the voltage and gearbox-output flywheel rotational-speed records were obtained separately, the two series cannot be correlated point by point.

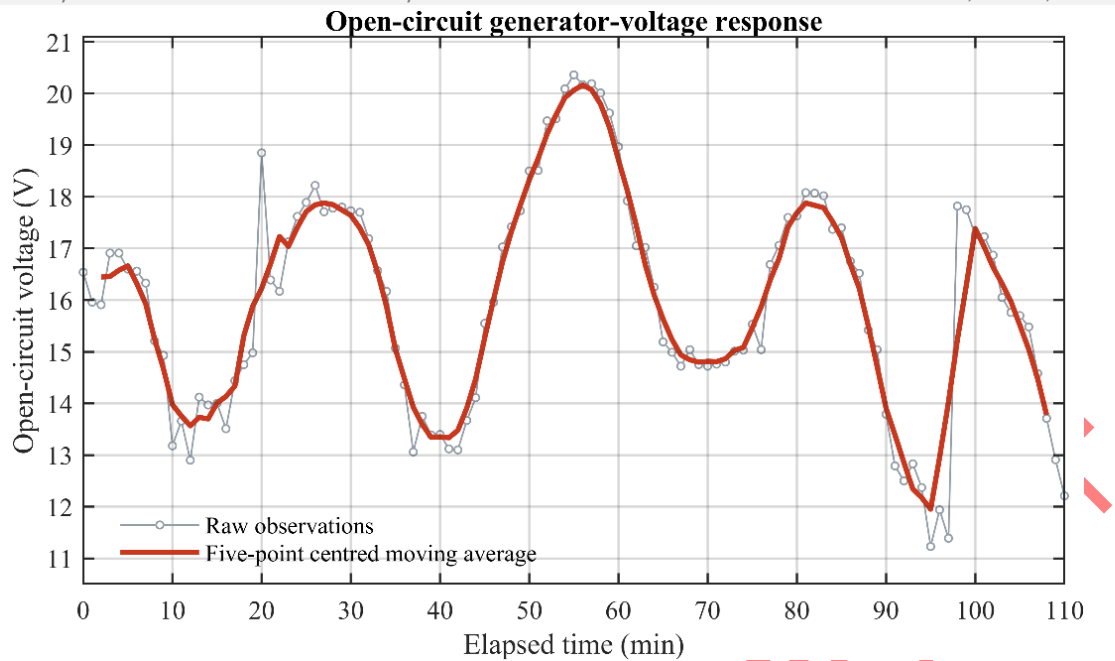


Figure 6. Open-circuit generator terminal voltage and five-point centred moving average during the separate 110-min full-scale on-site measurement run.

Table 1 summarises the descriptive statistics for the two independent operational measurement runs. The gearbox-output flywheel rotational-speed dataset comprises 52 observations collected over a 250-min measurement window, with values ranging from 63 to 359 rpm and a mean of 198.96 ± 76.89 rpm. The open-circuit generator terminal-voltage dataset comprises 111 observations collected during a separate 110-min measurement window, with values ranging from 11.23 to 20.36 V and a mean of 15.95 ± 2.12 V. Because the two datasets were acquired during separate, non-synchronised runs, they characterise the respective mechanical and electromechanical responses but do not establish a direct rotational-speed–voltage relationship.

Table 1. Descriptive statistics for the two independent operational measurement runs.

Indicator	Measurement window	n	Range	Mean $\pm$ standard deviation	Median
Gearbox-output flywheel rotational speed	250 min	52	63–359 rpm	198.96 ± 76.89 rpm	188 rpm
Open-circuit terminal voltage	110 min	111	11.23–20.36 V	15.95 ± 2.12 V	16.05 V

Note: *n* denotes the number of recorded observations. The rotational-speed and open-circuit terminal-voltage datasets were obtained from separate, non-synchronised measurement runs. Accordingly, their measurement windows and numbers of observations are independent, and the values should not be interpreted as paired measurements.

DISCUSSION

The observations are interpreted within the assessment boundary for this initial full-scale experiment. The pre-construction survey provides site and orientation context, and the two post-installation runs provide independent evidence of short-term field operability. Together, these records show that the system operated as intended in the nearshore environment. The records are not used to infer a quantitative wave-to-response relationship, hydrodynamic capture, wave-to-wire efficiency, regulated electrical output, grid compatibility, or readiness for power-supply deployment.

Evidence of Field Operability

Direct observation confirmed the intended operating sequence: the water-filled containers followed the local free-surface motion, the one-way mechanism transmitted the engaged downward stroke, and the return stroke occurred without reverse rotation on the common shaft. The measured gearbox-output flywheel rotation and the separately recorded generator terminal voltage extend this observation, showing that mechanical motion was transmitted through the gearbox and reached the coupled generator.

The main contribution is specific: the laboratory-derived, gravity-driven and phase-selective multi-unit architecture remained functionally active after transfer to full scale and installation in a naturally variable nearshore environment. The evidence combines pre-construction site observations with independent post-installation operational records; together, they demonstrate repeated functional activity rather than measured conversion performance.

Mechanical Interpretation

Equations (1)–(3) provide a reduced-order mechanical interpretation of the observed response. When the counterweight approximately balances the non-water moving mass, the enclosed seawater mass supplies the principal gravitational term during an engaged downward stroke. Spatially separated units can then distribute engagement events along the common shaft. The measured gearbox-output flywheel-speed fluctuations are consistent with repeated and potentially sequential engagement, but they do not uniquely demonstrate a phasing benefit, as unit-resolved motion and torque were not measured.

Rezaei et al. [31] experimentally evaluated a unidirectional mechanical power take-off that converted reciprocating motion into generator-driving rotation under external electrical loads. Their results support the mechanical plausibility of one-way rectification and show that conversion performance requires simultaneous measurements of force, speed, voltage, and load.

Electrical Interpretation

The non-zero open-circuit voltage observations indicate that mechanical motion reached the coupled generator during the voltage run. Open-circuit voltage nevertheless reflects generator excitation rather than delivered power. Without simultaneous loaded voltage and current, neither true electrical power nor power take-off efficiency can be calculated.

Dragić et al. [22] resolved power and efficiency during sea trials from measurements at six locations along a mechanical power take-off chain. Their approach illustrates the multi-location measurements required to separate losses between wave absorption, mechanical transmission, and grid delivery.

Ning et al. [45] demonstrated that resistive load changes the turbine-generator operating condition and the continuity of wave-to-wire conversion. The present no-load record therefore cannot represent generator behaviour under load, voltage regulation, or load-delivery capability.

Framework Boundaries

The evidence combines a single-day pre-construction observation window with separate short-duration post-installation operational runs. Because these records were not synchronised, the study cannot link the recorded wave range to individual gearbox-output flywheel-speed or terminal-voltage observations. It does not represent seasonal wave variability, monsoon transitions, extreme events, fatigue accumulation, or long-term mechanical degradation. The reduced-order framework also omits added mass, radiation and viscous damping, wave slamming, multidirectional wave groups, detailed transmission losses, and speed-dependent generator efficiency. These omissions restrict the framework to preliminary operability screening.

Cervelli *et al.* [12] quantified changes in device motion when multidirectional and monodirectional representations of irregular waves were compared. Their findings reinforce that the present phasing proxy is an assessment descriptor rather than a substitute for directionally resolved hydrodynamic analysis.

Lindén *et al.* [42] showed that corrosion and biofouling protection for wave-energy components depends on dedicated field protocols and validation of protective measures. The above-waterline location of the shaft and transmission components improves inspection access, but it does not by itself establish long-term material durability.

Further Validation

A subsequent validation phase would require synchronised measurements of wave elevation, unit displacement, shaft torque, rotational speed, loaded voltage, current, and true power. Repeated campaigns across seasons and extended marine exposure would provide evidence for reliability, structural wear, and operating-sequence stability. Unit-resolved measurements would also permit calibration of the loss and phasing factors within the assessment framework.

Chen *et al.* [27] progressed from scaled model testing to a full-scale, ten-absorber sea trial with monitored electrical production and grid connection. That progression shows the additional evidence needed to move the present work from short-term operability demonstration toward validated multi-unit power performance. Until comparable load-connected and long-duration evidence is available, the present findings support technical operability only.

CONCLUSION

This work establishes an operability-oriented framework for evaluating a gravity-based wave energy converter and supports it with an initial full-scale field demonstration. Pre-construction observations identified wave heights of 0.20–0.50 m, dominant periods of 3–6 s, and waves approaching predominantly from the west; these observations supported site selection and an approximately west–east platform orientation. After installation, separate operational runs recorded gearbox-output flywheel rotational speeds of 63–359 rpm and open-circuit generator terminal voltages of 11.23–20.36 V. Because the environmental and operational records were not synchronised, the results demonstrate short-term functional operability but do not quantify a wave-to-response relationship or regulated electrical output.

The framework treats enclosed seawater mass and multi-unit spatial phasing as candidate variables for interpreting the operating principle, but the present measurements did not resolve their individual effects. Subsequent validation requires synchronised measurements of waves, unit motion, torque, speed, loaded voltage, current, and true power; repeated campaigns across seasonal conditions; and long-duration assessment of corrosion, wear, fatigue, and structural reliability. Until such evidence is available, the findings support only technical operability, not readiness for power-supply deployment.

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USE OF ARTIFICIAL INTELLIGENCE

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NOMENCLATURE

Roman symbols

Symbol	Description	Unit
g	gravitational acceleration	m s^{-2}
G_s	spacing between adjacent converter units	m
h	deployment-site water depth	m
H_s	significant wave height	m
k_p	peak wavenumber	rad m^{-1}
M_c	effective non-water-moving mass of the converter unit	kg
M_{eff}	effective moving mass during engagement	kg
M_{gw}	enclosed seawater mass	kg
m_{cw}	counterweight mass	kg
N_{eff}	multi-unit effectiveness factor	—
T_p	spectral peak period	s
V_{dc}	open-circuit DC terminal voltage	V
V_w	enclosed seawater volume	m^3
W_{in}	gravitational input proxy	J

Greek symbols

Symbol	Description	Unit
$\Delta\phi_p$	characteristic phase spacing for the peak component	rad
η	aggregated loss factor	—
λ_p	representative wavelength associated with the peak period	m
ρ	seawater density	kg m^{-3}
ω_p	peak angular frequency	rad s^{-1}

Subscripts

Symbol	Description
c	non-water-moving component

Symbol	Description
<i>cw</i>	counterweight
<i>dc</i>	direct current
<i>eff</i>	effective value
<i>gw</i>	enclosed seawater mass term
<i>in</i>	input term
<i>p</i>	peak wave condition

Abbreviations

Abbreviation	Description
DC	Direct current
rpm	revolutions per minute

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